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Orbital Debris Wire Harness Failure Assessment for the Joint Polar Satellite System

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Abstract

The objective of this paper is to present the results of two hypervelocity impact failure risk assessments for critical wire bundles exposed aboard the Joint Polar Satellite System (JPSS-1) to an increased orbital debris environment at its 824 km, 98.8 deg inclination orbit. The first "generic" approach predicted the number of wires broken by orbital debris ejecta emerging from normal impact with multi-layer insulation (MLI) covering 36, 18, and 6 strand wire bundles at a 5 cm standoff using the Smooth Particle Hydrodynamic (SPH) code. This approach also included a mathematical approach for computing the probability that redundant wires were severed within the bundle. Based in part on the high computed risk of a critical wire bundle failure from the generic approach, an enhanced orbital debris protection design was examined, consisting of betacloth-reinforced MLI suspended at a 5 cm standoff over a seven layer betacloth and Kevlar blanket, draped over the exposed wire bundles. A second SPH-based risk assessment was conducted that also included the beneficial effects from the high (75 degree) obliquity of orbital debris impact owing to the flight orientation of the exposed wiring and shadowing by other spacecraft components. These factors resulted in a considerably reduced likelihood of critical wire bundle failure compared to the original baseline design with normal impacts and no shadowing.

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Keywords: MMOD, Hydrodynamic Code Simulation, Failure Risk Assessment

Nomenclature

MMOD Micrometeroid and orbital debris
ppi
pH
SEM

1. Introduction

NASA recently released a new orbital debris environment (ORDEM 3.0) that included an order of magnitude increase in particle counts in the 1mm size range, and a new component consisting of stainless steel particles, which are more dense and therefore more penetrating than the aluminum particles assumed in prior orbital debris models [1]. In light of this more hazardous environment, the NASA Engineering and Safety Council (NESC) sponsored an independent assessment of the orbital debris protection planned for the Joint Polar Satellite System (JPSS-1) in the summer of 2014. One of the initial findings of the NESC team was that no assessment of the risk to the spacecraft wiring had been included (this wiring is exposed to obital debris on the zenith deck of the spacecraft). Some of this wiring supported critical functions that would be required in order to assure re-entry of the satellite at the end of its life. As part of its support, several members of the NESC team developed and implemented a "generic" approach for determining the risk of critical function loss from hypervelocity

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impact and penetration of critical wire bundles from steel and aluminum orbital debris particles impacting in the 7.3 to 14.6 km/sec velocity range expected in the JPSS-1 orbit.

Based in part on the high computed risk of a critical wire bundle failure using the initial assessment approach, an enhanced orbital debris protection design was implemented, consisting of betacloth-reinforced MLI suspended at a 5 cm standoff over a seven layer betacloth and Kevlar blanket, draped over the exposed wire bundles. A second SPH-based risk assessment was conducted that also included the beneficial effects from the high (75 degree) obliquity of orbital debris impacts (owing to the tilt of the zenith-facing deck supporting the cable runs), and shadowing by other spacecraft components. This analysis resulted in a considerably reduced likelihood of critical wire bundle failure compared to the original baseline design. This second approach is consistent with earlier wire failure assessments for the James Webb Space Telescope [2] and other spacecraft such as the Advanced Xray Astrophysics Facility [3], which assumed that any penetration of the shield over the wire bundle caused failure of the bundle.

2. "Generic" Risk Assessment of Baseline MLI over Wire Bundles

The team performed SPHC hydrocode assessments of orbital debris penetration through a "typical" wire harness (cable) with baseline multi-layer insulation (MLI) blanket protection as shown in Figure 1. The SPHC (Smooth Particle Hydrodynamics in C) was developed by Stellingwerf (1985 – 1995). This code formed the basis of the SPHINX hydrocode package used at Los Alamos National Laboratory (Wingate 1995 – 1998). The present incarnation of SPHC, V12.8, runs up to one million particle problems on Windows ™ personal computers or work stations having 1.5 Gb of memory, without invoking virtual memory. In smooth particle hydrodynamics, the "particle" is the analog of the mesh point in a traditional hydrocode. An SPH particle consists of a fixed mass of a particular material at a given position in space, together with a smoothing function, or "kernel," that defines the particle's extent.

SPHC is a fully conservative code, meaning that mass, momentum, and angular momentum are exactly (analytically) conserved, and energy is conserved to the accuracy of the calculation. A Runge-Kutta integration scheme is used that allows specification of the timestep accuracy. The Mie-Grueneisen multi-phase equation of state (eos) in SPHC accepts the initial density and temperature of the material and computes the pressure, internal energy, phase and sound speed. In subsequent steps, the eos is used to compute the density and the internal energy, and then the resulting pressure, temperature, phase, and sound speed.

As shown in Figure 2, a typical cable is assumed to consist of 36 wires, or 18 redundant wire pairs. The wires were placed in a hexagonal pattern in order to scale the damage seen in 36 wires to smaller wire bundles (of 18 and 6 wires, respectively). It is noted that the actual hexagonal patterns undergoing hydrocode assessment were of 37, 19, and 7 wires, with damage to the last (deepest) wire neglected in the risk results for the 36, 18, and 6 wire strands. The risk assessment considered a one year exposure to the ORDEM 3.0 orbital debris environment, with particles striking normal to the lengths of the wires. A 5 cm standoff between baseline MLI and wire harness (cable) was included in the hydrocode run.

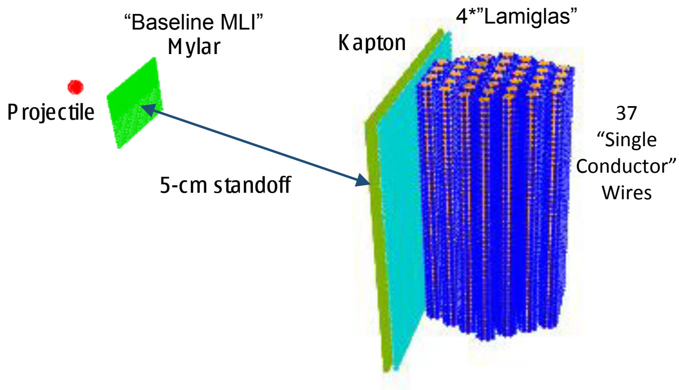

Fig. 1. JPSS-1 wire harness geometry, showing baseline MLI, 5-cm standoff, plus Kapton™ and Lamiglas™ cable wrapping materials.

Figure 2 shows a cross-section of the cable hex geometry, indicating how a cable of 37 single conducting wires can be broken down into 19-wire and 7-wire hexagonal component subcables, if desired. Also, the graphical means of indicating a cut or "killed" wire is shown. Results from the SPH analyses of the number of wires cut considering a variety of orbital debris impact materials, velocities and diameters are shown in Figure 3. Note that the expected number of penetrated wires increases with velocity, diameter, and density of the projectile. Figure 4 shows the likelihood of an entire cable failing based on the number of redundant wire failures. When more than half of the wires (i.e., 19 wires in a 36-wire bundle) are penetrated, there is a 100% chance that two redundant wires have been hit, thus killing the critical instrument that the wires are feeding.

Once the number of penetrated wires is predicted through SPH hydrocode assessment (and associated with a probability of cable failure, as shown in Figure 4), the analyst can determine the probability of those conditions occurring on orbit using NASA's Orbital Debris Environment Model, ORDEM 3.0 [4]. In our case, an Excel spreadsheet was developed that interpolates the size and velocity of steel and aluminum particles causing from 1 to 36 wire failures based on the hydrocode results, then calculates the likelihood of those particle combinations impacting normally on a one foot length of cable in a single year.

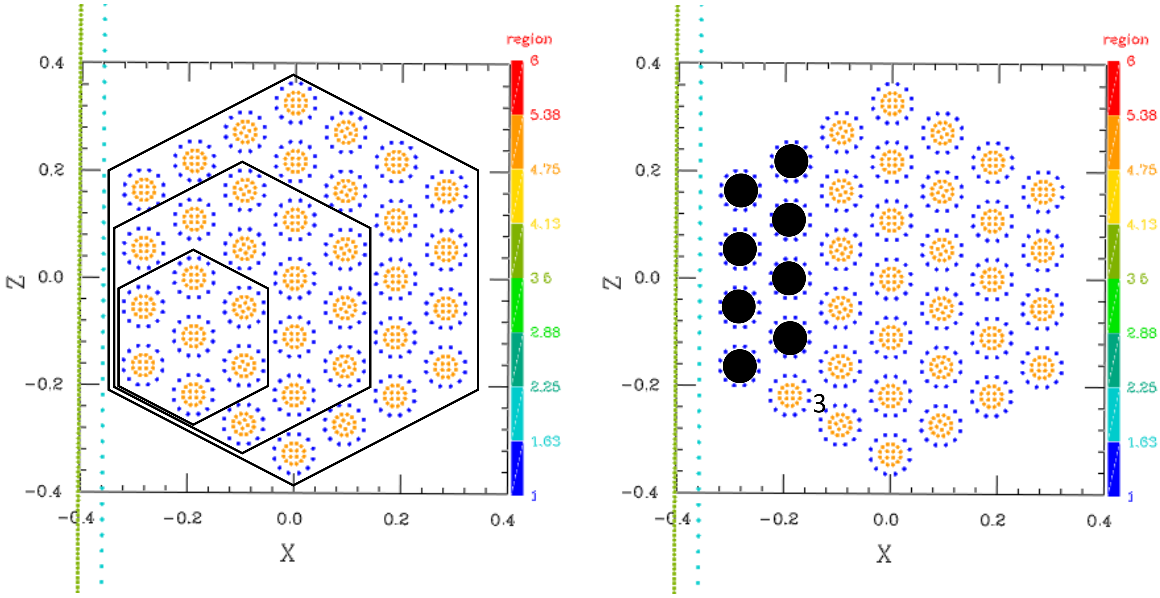

Fig. 2. 37-Hex wire cable arrangement, and subcables of 19 and 7 wires. "Killed" wires shown in black.

Table 1. shows the expected probability of orbital debris induced cable failure for a one year exposure of a one foot length of 6-, 18-, and 36-strand cables, where every strand within a cable carries a critical function and has a redundant wire somewhere in the cable carrying the same critical function. However, real spacecraft cables are often bundled together, shadowing one another, and are located and oriented where other spacecraft components shadow them from the debris flux. They also often carry less-than-critical functions. Table 2 shows that considering these effects of shadowing, position, and criticality can lower the likelihood of critical cable failure (for the 8 foot cable example) by a factor of 20.

3. Evaluating an Enhanced MMOD

Based in part on the high computed risk of a critical wire bundle failure from the generic approach, the JPSS program decided to implement an enhanced micrometeoroid and orbital debris (MMOD) protection design consisting of betacloth-reinforced MLI suspended at a 5 cm standoff over a seven layer betacloth and Kevlar blanket, draped over the exposed wire bundles, as shown in Figure 5. It is noteworthy that 99.5% of orbital debris approaches from within the X-Y (orbital) plane, and that orbital debris approaching from the Y axis (from the "front" as viewed by the spacecraft) makes up nearly 50% of this flux. This threat would impact the deck at 14.6 km/sec and impact the blanket at 75 degrees obliquity, relative to the exposed wires on the zenith deck. The ultimate objective was to develop a design that prevented penetration of 3mm aluminum spheres from the worst case impact conditions shown in Table 1.

As shown in Table 3, SPHC analyses showed that the enhanced shield was capable of preventing penetration of 3-mm aluminum and 2.12-mm steel orbital debris particles at the stated conditions.

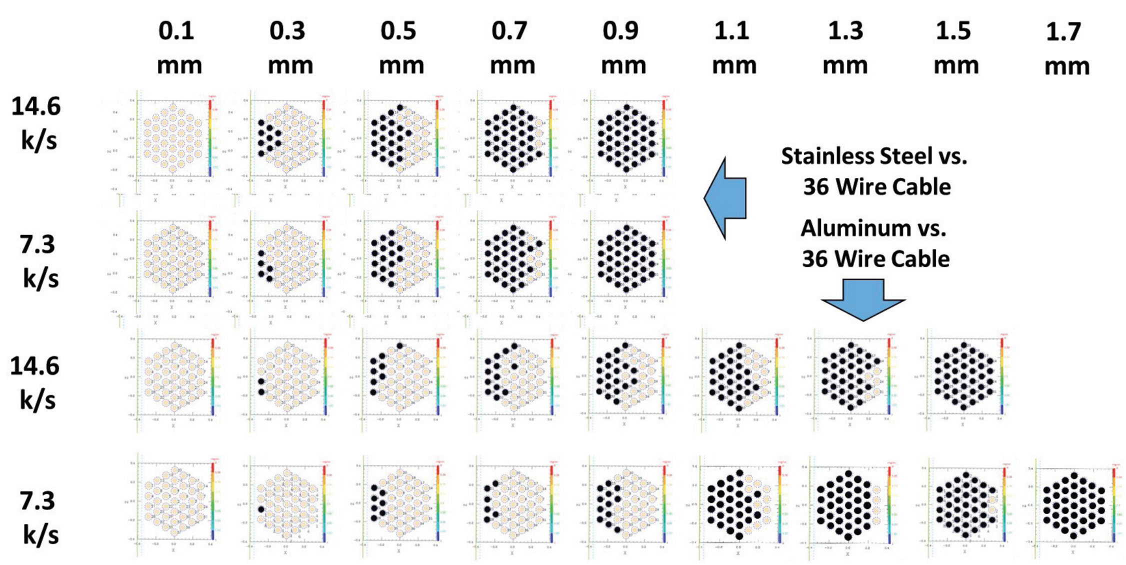

Fig. 3. Number of wires cut in 36-wire bundle for given combinations of orbital debris densities, diameters and velocities.

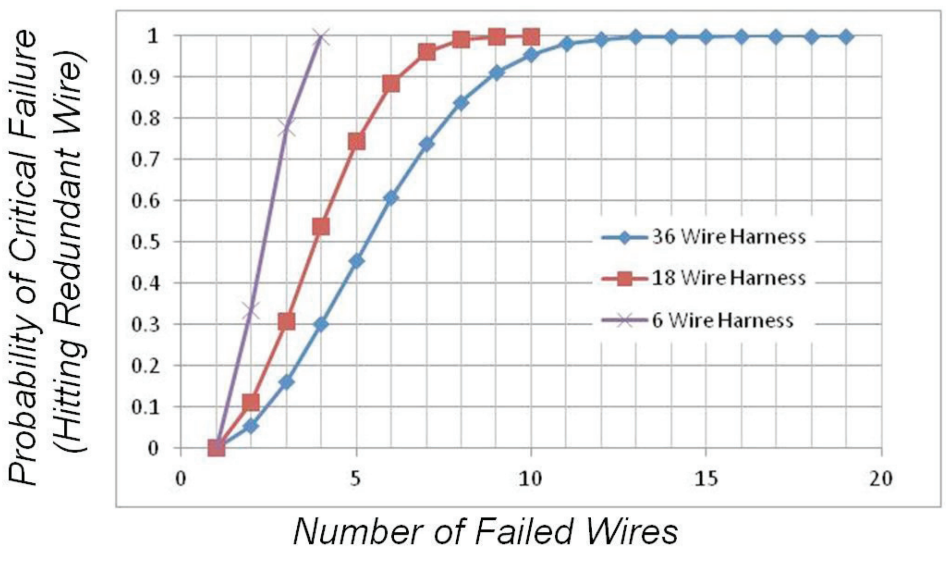

Fig. 4. Probability of critical failure vs. wire harness size given randomly placed redundant wire failure.

Table 1. Cumulative number of cable failures for three cable sizes (1 foot length, zentih/nadir orientation, 1 year exposure).

Bundle Size	Steel	Aluminum	Total
6	0.075	0.024	0.099
18	0.111	0.065	0.176
36	0.143	0.080	0.223

Table 2. Effect of shadowing and reduced criticality on a typical 8 foot cable.

Cable	Length (ft)	Baseline N Fails	Portside Shadowing	Ram Dir. Shadowing	45 deg Shadowing	Bundle Shadowing	Criticality	Realistic N Fails
1	2	0.446	0.5	0.46	0.84	1	0.5	0.043084
2	2	0.446	0.5	0.46	0.84	0	0.5	0
3	2	0.446	0.5	0.46	0.84	1	0.5	0.043084
4	2	0.446	0.5	0.46	0.84	0	0.5	0
	Baseline N Fails	1.784					Realistic N Fails in 8 ft	0.086
	Failure per foot	0.223					Realistic failures per foot	0.011
							Baseline / Realistic	20.7

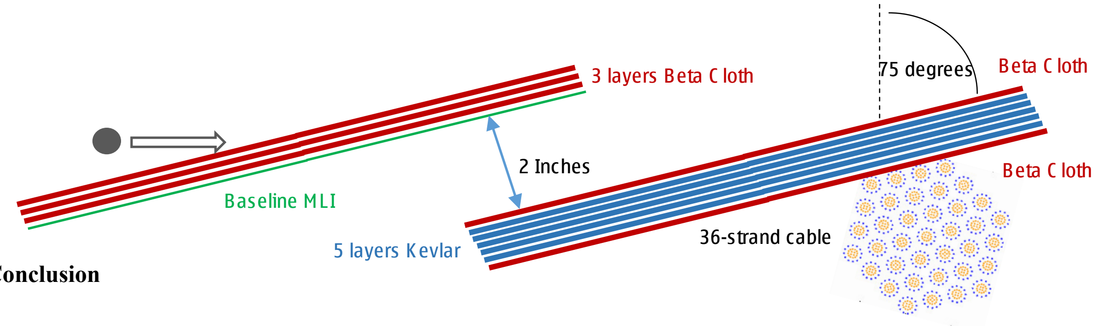

Fig. 5. Enhanced shield configuration for defeat of 3mm aluminum orbital debris particles.

Conclusion

Once the ballistic limit for the worst case orientation (and highest orbital debris flux) was determined using SPHC, the exposed area for the blanket (and wiring beneath it) was calculated using the configuration shown in Figure 5. The JPSS-1 spacecraft features radiators on the "sides" of the spacecraft that block much of the orbital debris from approaching the spacecraft from angles at 15 degrees or more from the velocity vector. Table 2 shows that there is a 5.3% probability that one or more orbital debris penetrations of the enhanced shield over the zenith deck wiring will occur in the expected 7 year operation of the JPSS-1 spacecraft. Most of this risk results from penetration by stainless steel particles, due to their lower ballistic limit and higher flux on the enhanced wiring shield.

Table 3. Orbital debris penetration risk for enhanced wiring shield.

Steel risk with shadowing					Aluminum risk with shadowing				
Approach Angle (deg)	BL for N	Pen Flx	Area	7 years N pens	Approach Angle (deg)	BL for N	Pen Flx	Area	7 years N pens
5	2.12	3.448e-3	0.562	1.356e-2	5	3.00	6.78e-4	0.562	2.669e-3
15	2.12	1.757e-3	0.488	6.001e-3	15	3.00	5.03e-4	0.488	1.718e-3
25	2.12	9.42e-4	0.272	1.793e-3	25	3.00	2.59e-4	0.272	4.932e-4
35	2.12	6.88e-4	0.098	4.722e-4	35	3.00	1.84e-4	0.098	1.262e-4
45	2.12	5.49e-4	0.042	1.614e-4	45	3.00	1.49e-4	0.042	4.387e-5
55	2.12	4.84e-4	0.013	4.405e-5	55	3.00	1.29e-4	0.013	1.173e-5
65	2.12	4.62e-4	0.005	1.616e-5	65	3.00	1.16e-4	0.005	4.072e-6
75	2.12	4.71e-4	0.0006	1.980e-6	75	3.00	1.14e-4	0.0006	4.803e-7
85	2.12	9.55e-5	0.0002	1.337e-7	85	3.00	6.57e-5	0.0002	9.192e-8
			Total	0.0441				Total	0.0101
			Ppen	**0.0431**				**Ppen**	**0.0101**

Summary and Conclusions

Two approaches were pursued to evaluate the risk from orbital debris penetration of exposed JPSS wiring. In the first case, a "generic" approach considering normal impact of the baseline MLI over wires resulted in an evaluation of wire damage that was very conservative, in that it did not consider the effects of obliquity, shadowing by other spacecraft components and adjoining wiring, and could not be sufficiently refined to account for the exact wiring bundle design, including redundancy.

In the second case, an enhanced orbital debris shield was evaluated to provide less than a 5.3% probability of penetration in seven years when placed over the exposed wires. However, shield penetration should not be equated to critical wire failure; the figure of 5.3% "risk" of shield penetration is an upper bound for critical wire failure risk, for the following reasons:

- Actual wire coverage is less than the coverage of the MMOD blanket (lowering critical wire risk),
- There is a higher ballistic limit of the shield at other approach angles, since that debris approaches at a lower velocity,
- Not every wire is critical, and many wires are redundant, and
- Many of the critical wires are placed below other wires, so more shadowing is likely than was accounted for in this assessment.

Considering these factors, the probability of critical wire failure on the zenith deck could be well below 1%.

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